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PARALLEL PLATE TRANSMISSION LINE POCKELS CELL

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INTRODUCTION

The ability to produce short-duration, high-peak-power laser pulses has many important consequences. Uses for Q-switched optical pulses include generating plasmas, optical harmonic generation, stimulated Raman, Brillouin, and Rayleigh-wing scattering, photon echos, self-induced optical transparency, optical self-trapping, and optical parametric amplification (1). Unfortunately, the required buildup time for a Q-switched optical pulse places a minimum pulse width limit of about 10^{-8} sec. This is not an acceptable lower limit for pulse width, since a large class of problems (1,2) (e.g., controlled thermonuclear plasma, optical radar, transient response of quantum systems, nonlinear optical properties of materials, etc.) requires pulses having time durations of 10^{-9} to 10^{-12} sec. One method of generating these extremely short-duration, high-peak-power pulses is to mode lock a laser (2). This technique yields a burst (or "train") of uniformly spaced pulses with nearly identical individual widths, varying from 10^{-9} to 10^{-12} sec depending on the laser cavity, active material, and method of mode locking. Since the spacing between the pulses (2) is twice the optical cavity length, an optical shutter with an open time of several nanoseconds may be used to select a single pulse from the train and thus provide a single laser pulse of picosecond length.

An alternate technique for producing a subnanosecond burst of light is to open an optical shutter for the desired length of time and "carve" a short pulse out of a longer laser pulse. This method (3) reliably creates pulses in the several hundred picosecond range.

Figure 1 shows a typical experimental arrangement for achieving subnanosecond pulses. The first polarizer defines a plane of polarization. The second polarizer is a glan-laser prism crossed to the first so that the beam is shunted off toward a spark gap which, when energized, connects a length of charged coaxial line to an electro-optical polarization rotator (4) such as a properly oriented Pockels cell. The high voltage is adjusted such that the pulse from the coaxial cable rotates the plane of polarization of the laser beam exactly 90°, thus allowing it to pass through the analyzer as desired.

Recently a laser-triggered spark gap (LTSG) was reported (3,5) which is capable of delivering rectangular voltage pulses exceeding 10 kV with a low delay and jitter, and having less than 10% ripple during and after the pulse. To properly utilize this LTSG, a parallel-plate, transmission line Pockels cell (TLPC) was constructed. By matching 50-ohm coaxial cable to the Pockels cell and terminating the line with a 50-Ω load, a single pulse has been reliably switched out from a mode-locked YAG laser output train while all other pulses in the train were attenuated by a factor of 1000.

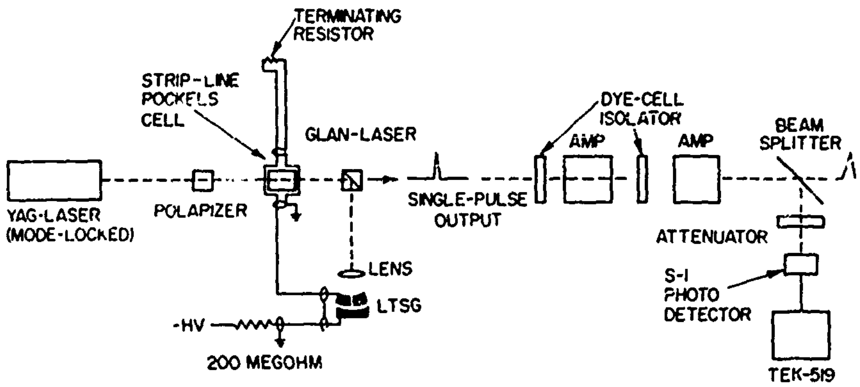


Fig. 1 — Experimental arrangement

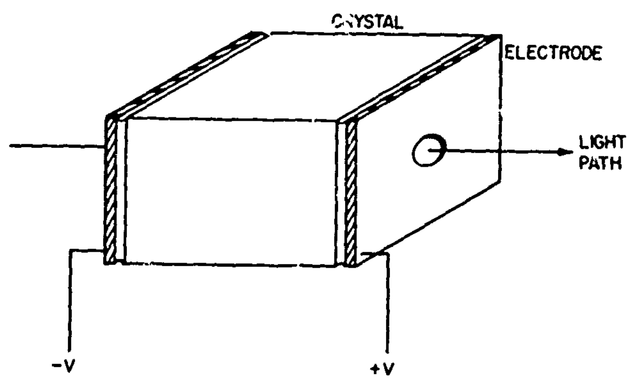


Fig. 2 — Longitudinal Pockels cell

THEORY AND DESIGN

Theoretical Considerations

A Pockels cell (Fig. 2) utilized in the longitudinal mode (6) typically consists of two electrodes placed at opposite ends and perpendicular to the optical axis of a uniaxial crystal which exhibits birefringence upon the application of an electric field. (The most commonly used crystals (6) for high-peak-power applications are KDP (KH_2PO_4), KD*P (KD_2PO_4), and ADP ($NH_4H_2PO_4$).) The optical signal is sent through the crystal parallel to the optical axis, and to the applied electric field. Transparent electrodes may be used for low-power signals, but for high-peak-power signals such as are obtained from mode-locked lasers it is necessary to cut apertures through the electrodes.

When used as a modulator or a switch, the Pockels cell is properly oriented (6) between crossed polarizers so that for zero voltage applied, no light is transmitted through the second polarizer, while for some voltage $V_{\lambda/2}$ (half-wave voltage) the plane of polarization of the light is shifted 90° in passing through the crystal and is 100% transmitted through the second polarizer.

The operating voltage $V_{\lambda/2}$ is then (theoretically) applied as a single square pulse whose rise time determines the opening time of the switch, and whose decay time determines the closing time.

A second method of operating such an optical switch is to charge the Pockels cell to $V_{\lambda/2}$ and arrange the polarizers in parallel so that at $V_{\lambda/2}$ there is no transmission of the light beam (of wavelength λ), while at zero voltage there is 100% transmission. The optical switch is then made transmitting by shorting out the voltage on the Pockels cell, and is closed by recharging the Pockels cell. Alternatively, one can apply a $2V_{\lambda/2}$ pulse to a cell charged to $-V_{\lambda/2}$, and thus drive the switch from closed, through an open state, and back to closed in the time it takes to charge the Pockels cell to $V_{\lambda/2}$.

The primary problems inherent in these designs are twofold. First, the induced birefringence is not perfect, so that when charged to $V_{\lambda/2}$ the isolation of the switch is reduced less than that obtained from zero voltage and crossed polarizers. Second, a Pockels cell in this mode is nothing more than a capacitor with very high Q, and charging or discharging such circuits rapidly always leads to ringing and resultant reduced isolation. On the other hand, when the Pockels cell is used as a section of transmission line, its opening and closing are limited only by the rise and fall times of the applied pulse and the propagation time of the voltage pulse across the cell aperture (about 10^{-10} sec for a 2-cm aperture).

In choosing a crystal for a longitudinal Pockels cell, the following considerations are very important:

1. The degree of optical transmission at the operating wavelength. This includes the damage threshold (surface and bulk) of the crystal vs the expected maximum expected power to which the Pockels cell is to be subjected.

2. Optical quality and size of crystals available. These quantities are related, as many crystals with high electro-optical coefficients have only been produced in high optical quality for very small crystals (e.g., CuCl).

3. The electro optical coefficients. For crystals of the class $\bar{4}2$ m used in the longitudinal mode, it is sufficient to consider r_{63} (7). Included in these considerations are the amount of voltage required for half-wave retardation of the "extraordinary" wave with respect to the "ordinary" wave, and the temperature dependence of the electro-optical coefficient at the desired operating temperature. Although r_{63} increases drastically in the vicinity of the Curie temperature T_c, it becomes too sensitive to temperatures change to be considered a good operating point for most applications.

4. The electrical properties. The relative dielectric constant ϵ determines the capacitance of the crystal and thus the power required to drive it. The loss tangent (tan δ) and electrical relativity ρ are important in estimating the amount of energy which will be deposited in the crystal electrically in any given situation.

5. The crystal properties. These include hardness, photoelastic and piezoelectric properties, solubility, thermal conductivity, and stability.

At present, probably the most useful crystal for making Pockels cells is KD*P. It has an r_{63} of from 20 to 26 $\times$ 10^{-12} m/V depending on the degree of deuteration. The value of r_{63} for KDP is only about 10.3 $\times$ 10^{-12} m/V. This means that the much

cheaper KDP requires twice the field strength for the same effect at any given wavelength. In the 1-μ range with a 3/4-in. crystal one is speaking of the difference between applying 12 kV (KD*P) and 25 kV (KDP). Thus, KD*P is used if possible.

Excellent discussions on the crystallographic principles of electro-optic modulation are contained in Refs. 6 and 7. In addition, Ref. 7 contains an extensive review and compilation of important materials properties of 13 electro-optic materials used in Pockels cells. For uniaxial crystals such as KD*P (potassium dideuterium phosphate), there is theoretically no birefringence along the optical axis. In practice these crystals have a small residual birefringence, and also, the optical axis cannot be perfectly located. Commercially available Pockels cells usually have advertised contrast ratios between crossed polarizers ranging from 200:1 to 1000:1, depending on price. It should be noted that such figures are usually obtained under extremely favorable conditions. These figures are strongly alignment dependent and are also sensitive to the type of drive voltage applied to the Pockels cell. It should be remembered that for any electrical network there is a great deal of difference between its response to a fairly steady sine wave and its response to a single impulse function.

If V is the applied voltage and I_0 is the intensity of the signal transmitted by the first polarizer, then the intensity of the light passed by the second polarizer (neglecting surface reflections, scattering losses, etc.) is

$$I(V, \lambda) = I_0 \sin^2 \left[\frac{\pi}{2} \frac{V}{V_{\lambda/2}}\right]. \tag{1}$$

A mode-locked laser output pulse (Fig. 3, lower signal) typically consists of a series of equally spaced high-peak-power pulses (1). Pulse widths are normally much less than 10^{-9} sec, while the spacing between pulses (twice the optical length of the oscillator cavity) is on the order of 5 to 10 nsec. By tailoring and time synchronizing the voltage pulse driving the Pockels cell as in Fig. 3, a single pulse may be removed from the train of pulses.

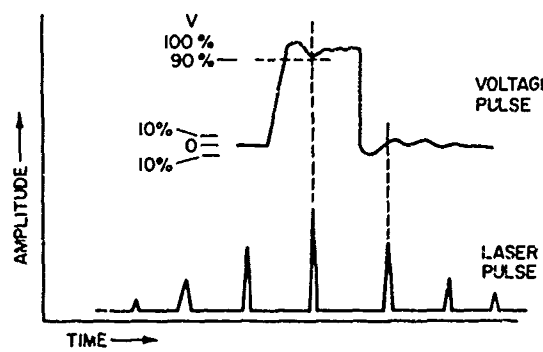


Fig. 3 — Single pulse split out, worst case

Thus, for $V = 0.9\ V_{\lambda/2}$, $I(0.9\ V_{\lambda/2}, \lambda) \approx 97.5\%$ while for $V = 0.1\ V_{\lambda/2}$, $I(0.1\ V_{\lambda/2}, \lambda) \approx 2.5\%$. Therefore, for a perfect Pockels cell and a worst-case location (Fig. 3) of the mode-locked pulses the isolation would be approximately 39 to 1.

Actually in practice there are enough parameters at hand to insure against the occurrence of the worst case. By increasing cavity length, the spacing between the pulses may be lengthened, and the electrical pulse length may be tailored to any desired length. The work of Bettis and Guenther (4) shows very definitely that the rule for low delay and jitter in a laser-triggered spark gap is high pressures and small gap spacing. Figure 4 gives four curves from their paper showing the steep dependence of delay and jitter on the percentage of V_{sB} (self-breakdown voltage of the gap) applied to the gap and on the laser energy. Since we use our spark gap at 90% of V_{sB} and gaps of 0.8 mm, subnanosecond jitter is easily obtained. To adjust delay, an electrical time delay (length of RG-8) may be inserted between the spark gap and the Pockels cell to open the Pockels cell at the correct time. By using a 5-nsec drive pulse to the Pockels cell, 9 nsec between the pulses of the mode-locked train, and setting the delay so that the electrical pulse arrives at the Pockels cell 1.5 nsec after the pulse which fired the LTSG, the desired pulse is assured of passage in a low-ripple region of the electrical pulse (i.e., 2.5 to 4.5 nsec after the leading edge) and the following optical pulse arrives at the Pockels cell after the ringing from the closing of the gap has died down (i.e., 2.5 nsec or more). Thus the 39-to-1 isolation for the worst case of the above paragraph is not encountered in careful practice, and the actual isolation is more a function of careful alignment of the crossed polarizer and the depolarization introduced by the Pockels cell in a static situation.

In Fig. 5a, the normal use of a Pockels cell is shown. Since the Pockels cell introduces a large impedance discontinuity at a point ℓ (electrical length) from the spark gap, a relatively large portion of the original signal will be reflected back toward the gap. When it arrives at the gap it finds an open circuit (gap deionized again), suffers a voltage and direction reversal, and propagates back down the line to the Pockels cell again. Unfortunately, the second mode-locked pulse after the desired pulse arrives at the Pockels cell at about the same time as the reflection and finds the Pockels cell partially on. From Eq. (1) it can be seen that for a 25% reflection of the voltage pulse, the later optical pulse will be approximately 15% transmitted. Since in many systems the intensity of this pulse is within 10% or less of the desired pulse, this can reduce the isolation to the order of 7 to 1.

The question naturally arises, is 25% reflection a reasonable value to assume? For a transmission line (8) of impedance Z_0 terminated by a resistance R, the reflection coefficient ρ is given by

$$\frac{\text{reflected wave}}{\text{incident wave}} = \rho = \frac{Z_0 - R}{Z_0 + R}. \qquad (2)$$

Solving (2) for ρ we find that $R/Z_0 = 0.6$. Therefore a 52-ohm transmission line (RG-8) terminated by a 31-ohm resistance would yield a 25% reflected signal. Since the impedance of coaxial cable is $Z_0 = \sqrt{L/C}$ and RG-8 has a $C \approx 30$ pF/ft capacitance, a Pockels cell with an effective capacitance of 10 pF (see next section) would certainly change the impedance at its intersection with the line by more than a factor of 0.6.

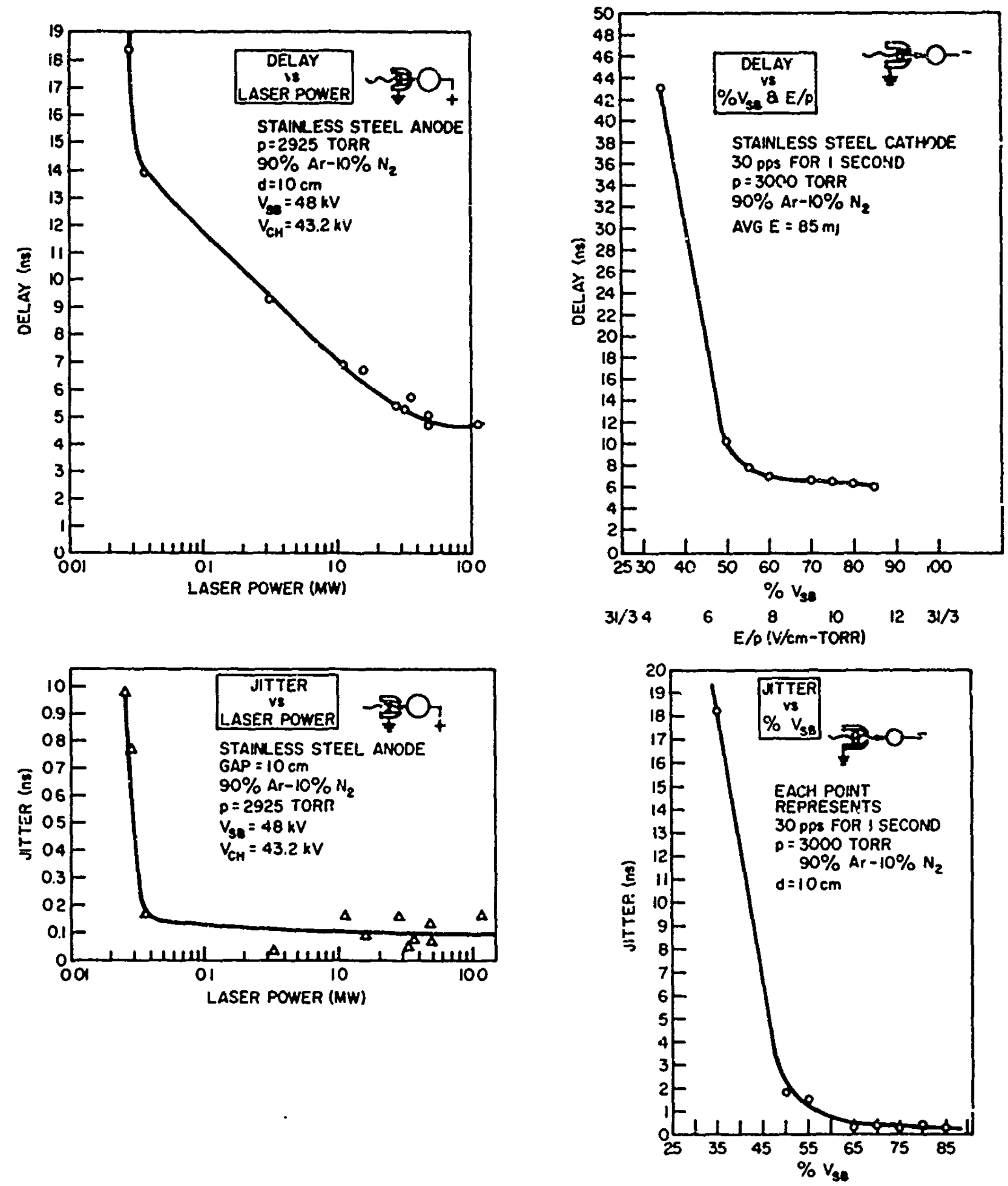


Fig. 4 — Curves from Ref. 4

Looking at Fig. 6 and using Eq. (2), we can see that if the Pockels cell can be made to represent a 2-terminal network having an input and an output impedance identical to the transmission line it is to be used with, then no reflection will occur and the Pockels cell will only be energized for the desired optical pulse. An easy way to accomplish this is to construct the Pockels cell in the form of a parallel-plate transmission line.

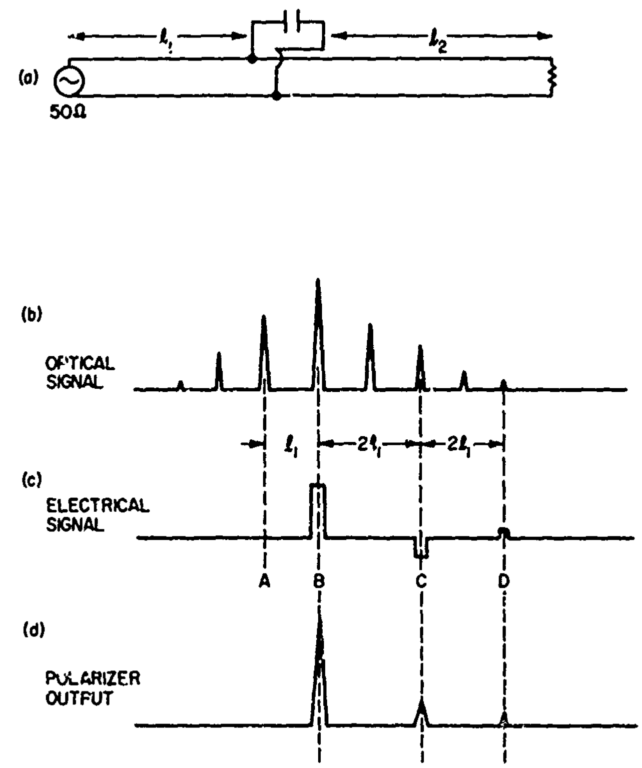


Fig. 5 — Typical Pockels cell arrangement

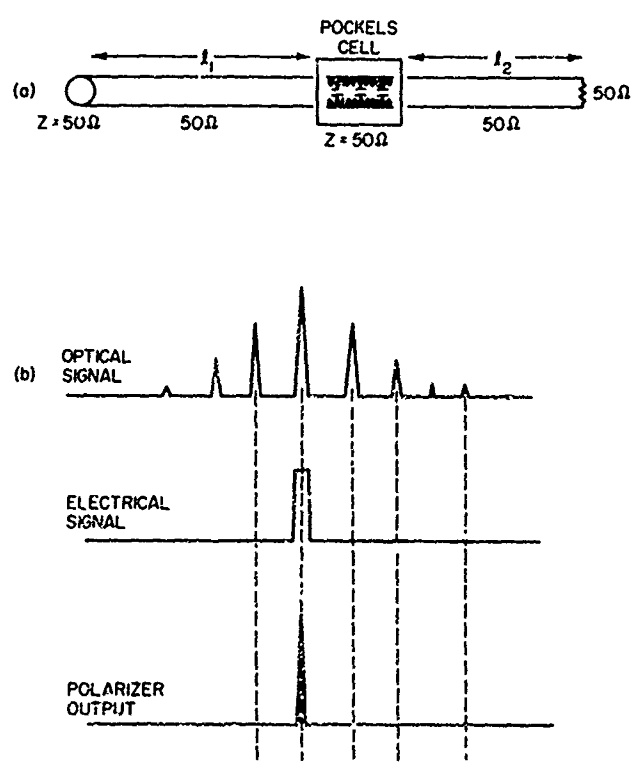


Fig. 6 — Stripline Pockels cell arrangement

For an ideal parallel-plate line, the characteristic impedance is given by (9)

$$Z_0 = \frac{b}{a} \frac{377}{\sqrt{\epsilon}} \text{ ohms,} \tag{3}$$

where

b = spacing between conductor plates

a = width of plates

ϵ = relative dielectric constant of the dielectric material between the plates.

Equation (3) assumes no edge effects. For closely spaced plates this is a valid approximation as long as the ratio of $b/a\sqrt{\epsilon}$ is kept less than 0.1. For 50-ohm lines, $b/a\sqrt{\epsilon}$ is 0.133, which means the approximation is not quite valid.

To test the approximation in the region in which we are working, we can measure the capacitance of our section of parallel plate line. For a section of length a, neglecting edge effects, the capacitance is given by (10)

$$C = 0.0885\, \epsilon \frac{a^2}{b} \text{ pF,} \tag{4}$$

where a and b are in centimeters. Since this square capacitor has twice the edge length as when it was a transmission line, it should be affected twice as much. Thus, if C is the calculated capacitance, and C′ is the measured capacitance, for small errors we can set

$$C' = C\,(1 + \gamma)$$

and (5)

$$\gamma = (C'/C - 1).$$

Then the effect for just two edges is

$$C'' = C(1 + \gamma/2),$$

and the capacitance per unit length is just

$$\hat{C} = 0.0885\, \epsilon\, a/b\, (1 + \gamma/2) \text{ pF/cm.}$$

Since the inductance L per unit length is inversely proportional to the capacitance per unit length (9), and since $Z_0 = \sqrt{L/C}$, the actual characteristic impedance Z_0' should be given by

$$Z_0' = Z_0/(1 + \gamma/2). \tag{6}$$

Design

In Fig. 7, b is the spacing for the stripline crossing the crystal, and b′ for the stripline leading into and out of the Pockels cell. Similarly, a and a′ are the respective widths, while

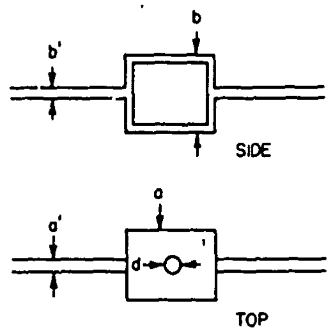


Fig. 7 — Pockels cell schematic

d is the diameter of the aperture through which the optical beam passes. For homogeneity of the electric field in the path of the optical beam and to minimize the impedance disruption in the stripline, it is best to make the ratio of a to d as large as is consistent with the size of the laser beam and the economics of high-optical-quality electro-optic crystals.

Once the value of a is established, the value of b can be computed from Eq. (3). For 50-ohm lines, the ratio of b to $a\sqrt{\epsilon}$ is close enough to 0.1 to allow the use of Eq. (3) without correction (see experimental section).

The choice of b′ is dependent on the type of connector to be used and the peak voltage to be applied. Since air has a breakdown voltage of about 75 V/mil (10), it is better to use a dielectric spacer which has a better breakdown voltage (e.g. Dow Corning 184 resin, 550 V/mil). The advantage of a silicone resin is that the crystal can be encapsulated in it at the same time the stripline is being formed, thus physically connecting the stripline spacer to the crystal.

Once b′ is chosen, a′ is calculated using b′ and the dielectric constant of the stripline spacer in (Fig. 9).

Similarly, b″ is determined by the spacing already present in the connection or coaxial line entering and leaving the stripline, and the a″ is calculated using Eq. (3).

It must be emphasized that there is nothing magical about the actual values of a and b. Only the ratio is important, and if either a or b is limited by some constraint (such as peak voltage or physical size), one needs only to adjust the unrestricted value to achieve the desired ratio.

As the more popular electro-optical materials such as KDP and ADP are hygroscopic, it is usually best to clamp and seal windows over the entrance and exit apertures. The physical stress placed upon the crystal thus serves to damp the piezoelectric resonance which accompanies the electro-optic effect.

Finally, the window holders and the input/output connectors should be rigidly connected to the same housing to prevent relative motion of the stripline plates and the electro-optical crystal.

EXPERIMENTAL RESULTS

A stripline Pockels cell was designed and built for use with a mode-locked YAG laser. A KD*P crystal from an Isomet EOA-415BX Pockels cell was used (Fig. 8). No attempt was made to correct the size of the crystal since the electrodes and windows were already attached and had good optical surfaces. The electrodes were 1.00 in. on a side with a 0.500-in. aperture, and the crystal was 0.750 in. long. The KD*P was better than 99% deuterated, and the Isomet reported the dielectric constant to be between 50 and 52.

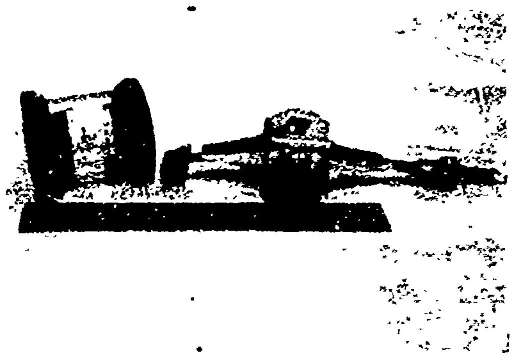


Fig. 8 — Isomet KD*P crystal

The capacitance of the cell as computed by Eq. (4) was 15.2 pF. When the capacitance of the aperture was subtracted, a theoretical capacitance of 12.2 pF resulted. Since the measured capacitance was 12.4 pF, the edging was assumed to have no effect on the impedance.

From Eq. (3), the input/output impedance of the Pockels cell as a transmission line was computed to be 39.9 ohms. To compensate for this, the stripline connecting the crystal to an RG-58C cable was tapered so as to be 50 ohms at the cable and 40 ohms at the crystal (Fig. 9). This was done because smooth transitions reflect much less than abrupt ones. The length of the transition is less than is desirable, but this choice was made for compactness. The final dimensions of the stripline Pockels cell are listed on Fig. 9.

Figure 10a through g consists of reflection measurements using a Tektronix time-domain reflectometry system which has a 25-psec response time. Figure 10a compares the original Isomet Pockels cell (top) with a 10-pF ceramic disc capacitor (bottom) having 1-5/8-in. leads. The time scale is 0.5 nsec per division.

Figures 10b, c, d, and e are 1 nsec per division with a vertical gain of 100 mV per division. They show respectively an open, a short, a 50-ohm termination supplied with the time-domain reflectometer (TDR) system, and the stripline Pockels cell followed by a 50-ohm cable. The trace starts approximately centered on the graticule at the 50-ohm value set by the incoming line. About 0.4 nsec after the start of the grid, the system under test is encountered. This yields a jump in the trace, which is a measure of the discontinuity. Note that, although the 50-ohm load yields a continuation of the trace

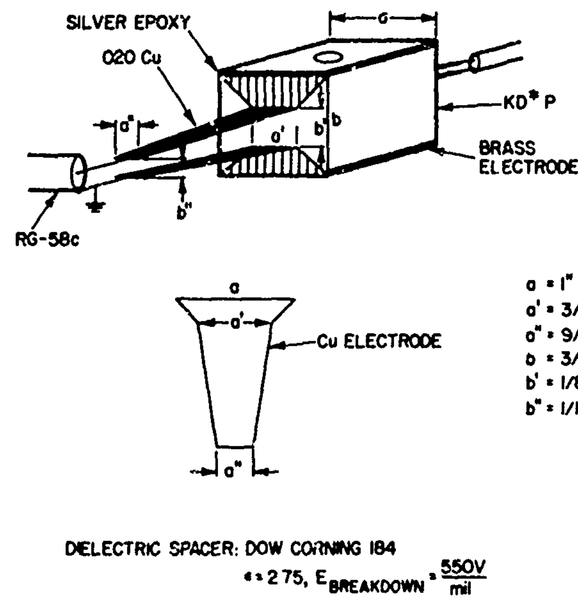


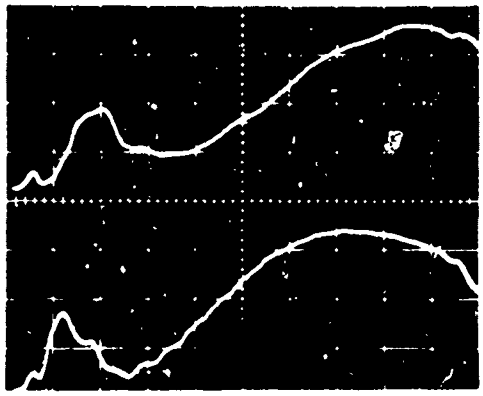
Fig. 9 — Stripline Pockels cell, final construction

along the 50-ohm level (Fig. 10d), the TDR system is able to resolve the discontinuity introduced by the 50-Ω BNC connector.

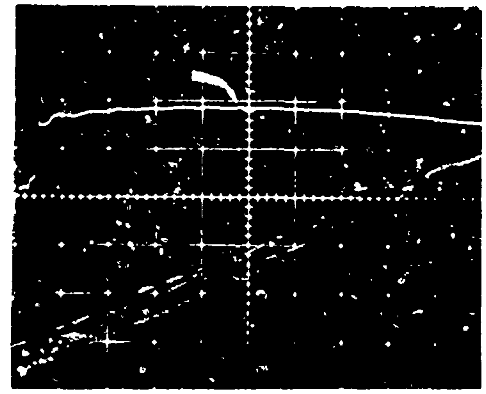
Figures 10f and g again compare the 50-ohm load (Fig. 10f) and the stripline Pockels cell (Fig. 10a), this time at 0.5 nsec per division and a gain of 20 mV per division. As can be seen from Fig. 10f, a large portion of the reflection comes from the poor response of the BNC connectors to very short pulses. A later version will utilize GR connectors in place of the BNC connectors. Also, a poor job of connecting the stripline to the crystal gave the large mismatch at the crystal-stripline interface. In spite of these mistakes, the Pockels cell worked so well that it was not worthwhile to disassemble and remake it.

Figure 11 is a Tektronix 519 scope trace typical of a split-out pulse from a mode-locked YAG laser and two YAG amplifiers using a S-1 detector (Fig. 1 shows the experimental setup). The square pulse driving the Pockels cell is about 3.5 nsec; the spacing between spikes in the mode-locked train is about 6 nsec. The long amount of ripple following the single pulse is electrical interference from the spark gap; it appears on the trace even when the detector entrance is blocked.

Figure 12a shows the optical signal leaking through the Glan-laser prism when the spark is not fired. This signal has about 1/1000 of the peak amplitude of the single pulse which comes through when the spark gap is fired (Fig. 11 has a 28-dB attenuation inserted). The causes of imperfect contrast are poor alignment, natural birefringence in the KD*P, and crossed prism leakage. Figure 12b shows the electrical interference when no optical signal is allowed to reach the detector. Figure 12c, at twice the sweep speed but with the same attenuation as 12a, shows the amplitude of the pulse adjacent to the "single" pulse. This procedure is not recommended as it can destroy a detector in a few



(a)



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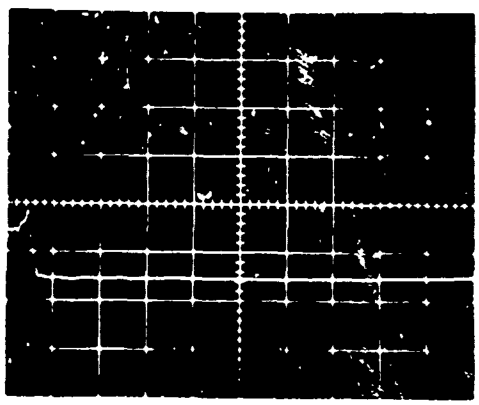

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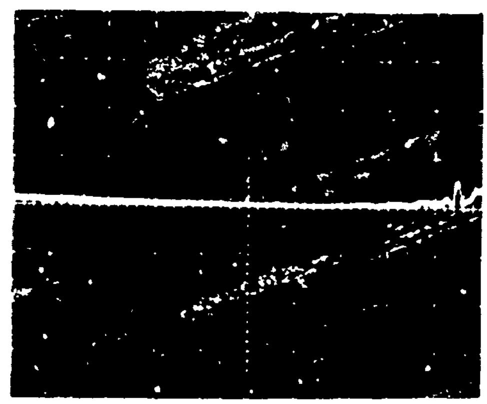

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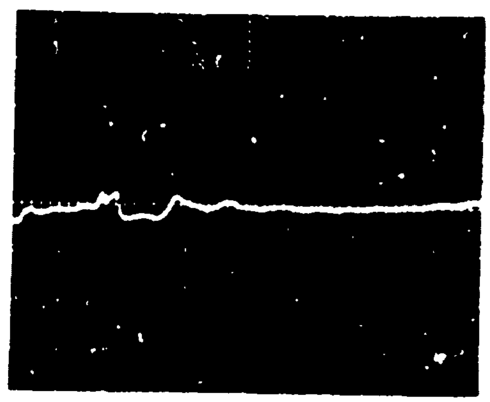

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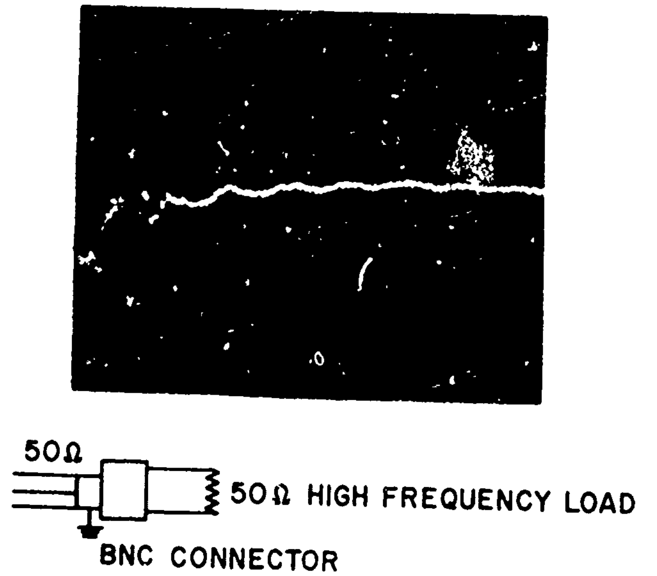
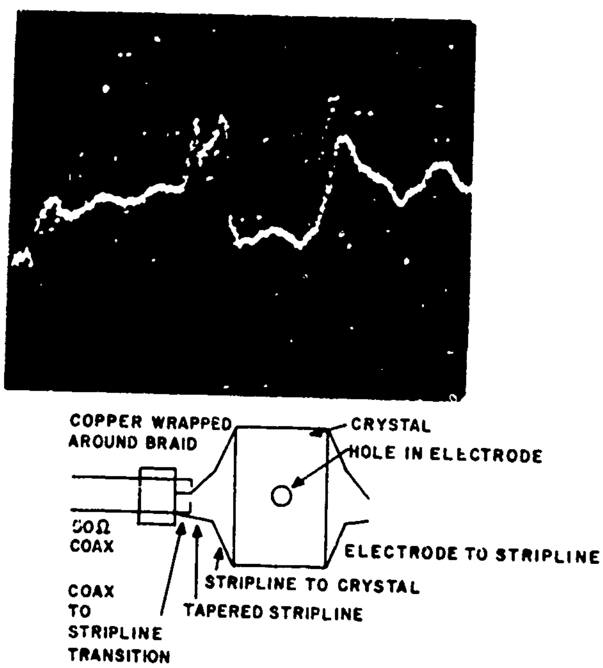


(f)



(g)

Fig. 10a-g — TDR pictures

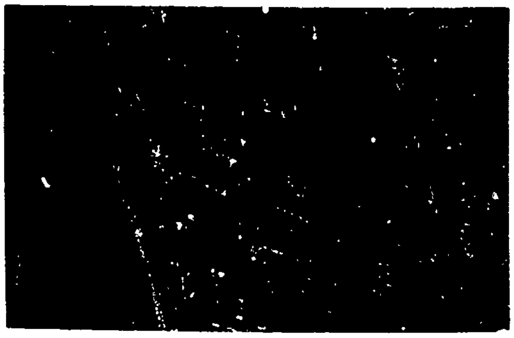
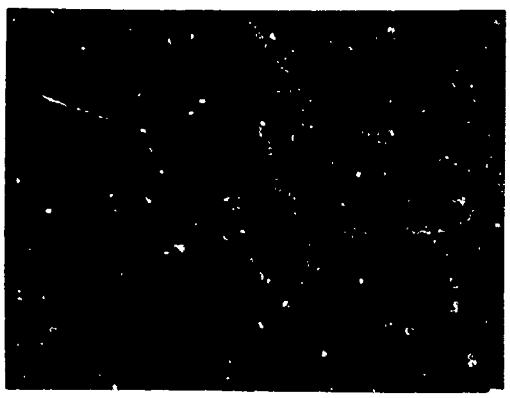
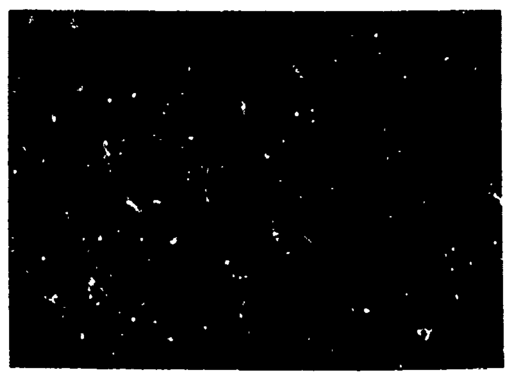


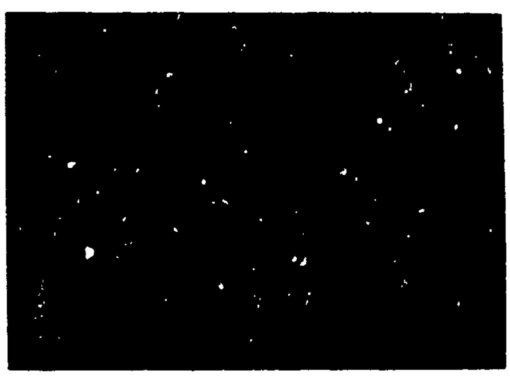
Fig. 11 — Typical single-pulse oscilloscope



(a)



(b)



(c)

Fig. 12a-c — Single-pulse isolation, oscilloscope pictures

shots, but it clearly shows that the loss of contrast caused by reflected electrical pulses from the stripline Pockels cell is better than 1000 to 1.

SUMMARY

It has been demonstrated that it is possible to construct a stripline Pockels cell based on very simple considerations which will operate well with laser-triggered spark gaps. Contrast ratios of a least 1000 to 1 have been achieved without excessive difficulty, and it appears that with effort an even better contrast ratio could be achieved.

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